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PLATE I

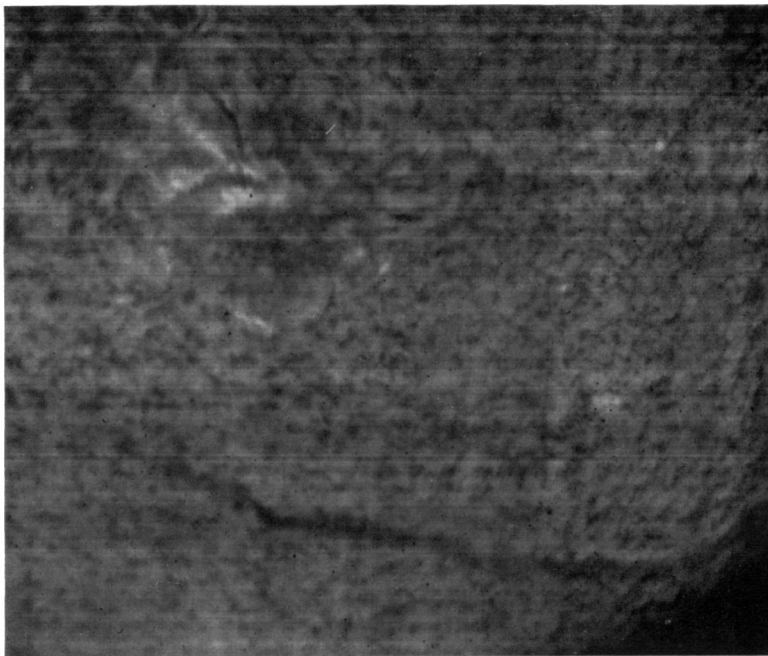


FIG. 1.—HYDROGEN FLOCCULI, PHOTOGRAPHED WITH THE $H\alpha$ LINE
1908, May 1, 4^h 48^m P. M. Scale: Sun's Diameter = 0.2 Meter



FIG. 2.—HYDROGEN FLOCCULI, PHOTOGRAPHED WITH THE $H\delta$ LINE
1908, May 1, 5^h 07^m P. M. Scale: Sun's Diameter = 0.2 Meter

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SOLAR VORTICES.¹

BY GEORGE E. HALE.

The problem of interpreting the complex solar phenomena recorded by the spectroheliograph has occupied my attention since the first work with this instrument in 1892. The measurement of the daily motions in longitude of the calcium flocculi has led to several new determinations of the solar rotation,² and their areas, measured by a photometric method, are being used as an index to the solar activity. Various investigations on their forms at different levels,³ their distribution in latitude and longitude, etc., have also been carried out. But the failure of the calcium flocculi to indicate the existence of definite currents in the solar atmosphere has been a disappointment.

The hydrogen flocculi, though occupying the same general regions on the Sun's disk, are distinguished from those of calcium by several striking peculiarities. In the first place, most of them are dark, while the corresponding calcium (H_2) flocculi are bright. Secondly, as I have recently shown,⁴ they seem to obey a different law of rotation, in which the equatorial acceleration (better, the polar retardation) shared by the spots, faculæ and calcium flocculi, does not appear. A third peculiarity, briefly mentioned in previous papers, is

¹ *Contributions from the Mount Wilson Solar Observatory*, No. 26.

² HALE and FOX, "The Rotation of the Sun, as Determined from the Motions of the Calcium Flocculi," Carnegie Institution (in press). FOX, *Science*, April 19, 1907. HALE, *Contributions from the Mount Wilson Solar Observatory*, No. 25; *Astrophysical Journal*, Vol. XXVII, p. 219, 1908.

³ HALE and ELLERMAN, *Publications of the Yerkes Observatory*, Vol. III, Part I.

⁴ HALE, *Contributions from the Mount Wilson Solar Observatory*, No. 25; *Astrophysical Journal*, Vol. XXVII, p. 219, 1908.

clearly visible on many hydrogen photographs. It is a decided definiteness of structure, indicated by radial or curving lines, or by some such distribution of the minor flocculi as iron filings present in a magnetic field (see, for example, *Astrophysical Journal*, Vol. XIX, Plates X and XII). First recognized at the beginning of our work with the hydrogen lines in 1903, this suggestive structure has repeatedly shown itself on the Mt. Wilson negatives. But its true meaning did not appear until the results described in this paper had been obtained.

With the Rumford spectroheliograph the hydrogen lines $H\beta$, $H\gamma$, and $H\delta$ were used. Certain differences between the photographs, which seemed to depend upon the wave-length, pointed to the desirability of trying $H\alpha$. But plates sufficiently sensitive to red light were not to be had at that time, and therefore the experiment was postponed.

The extreme sensitiveness in the red of plates prepared according to a formula due to WALLACE¹ now renders it a simple matter to photograph the Sun with $H\alpha$. Some preliminary work with the spectroheliograph attachment of the 30-foot Littrow spectrograph of the tower telescope, in which I had the assistance of Mr. ADAMS, indicated that bright flocculi are more numerous and extensive when photographed with $H\alpha$ than when $H\delta$ is used. I then tried $H\alpha$ with the five-foot spectroheliograph of the Snow telescope, and immediately obtained excellent results. The images were stronger and of much better contrast than those given by $H\delta$. Moreover, the curved and radial structure surrounding sun-spots was so striking as to lead to the hope that important advances might be expected to follow from the systematic use of the $H\alpha$ line.

On account of the difference in curvature of $H\alpha$ and $H\delta$, these preliminary photographs, made with $H\delta$ slits, showed only a very narrow zone of the solar image. A new pair of slits, of suitable curvature for $H\alpha$, was accordingly made for the five-foot spectroheliograph, and as soon as these were ready I completed the adjustments of the instrument, with Mr. ELLERMAN'S assistance, and made comparative photo-

¹ *Astrophysical Journal*, Vol. XXVI, p. 299.

PLATE II

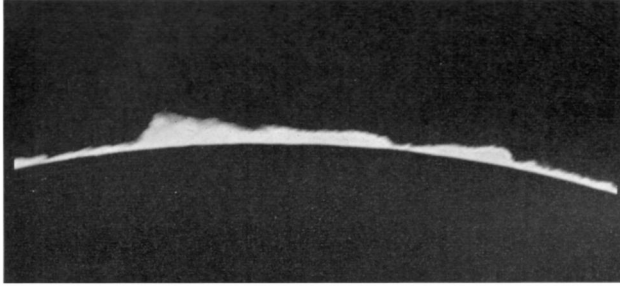
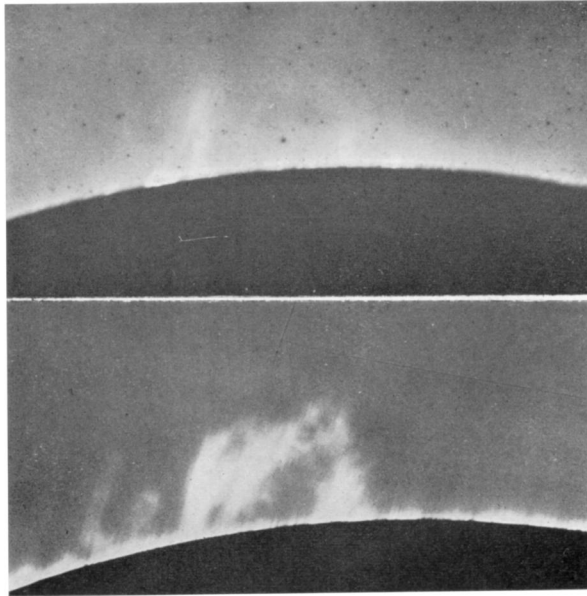


FIG. 1.—PROMINENCES AT EASTERN LIMB OF THE SUN
1908, May 26, 6^h 38^m A. M. Scale: Sun's Diameter = 0.3 Mete.



FIGS. 2 AND 3.—PROMINENCES PHOTOGRAPHED WITH $H\delta$ (FIG. 2) AND $H\alpha$ (FIG. 3)
1908, April 3. Scale: Sun's Diameter = 0.3 Meter

graphs of the entire disk with $H\alpha$ and $H\delta$. The differences exhibited by these plates are very marked. For example, a long dark flocculus, strongly shown by $H\alpha$, is represented on an $H\delta$ photograph by only a few of its most intense parts. In the case of bright flocculi, the differences are even more conspicuous, large luminous areas shown by $H\alpha$ being absent from the $H\delta$ plates. To eliminate errors arising from possible changes on the Sun between exposures, the photographs were taken in rapid succession, an $H\alpha$ plate between two of $H\delta$. In this way all doubts as to the genuineness of the observed differences were removed. Plate I illustrates the general character of these differences, concerning the cause of which we may now inquire.

It naturally occurred to me that photographs of a prominence at the Sun's limb, taken with the various hydrogen lines, would be likely to throw light on the question. Mr. ELLERMAN accordingly made a series of photographs of a prominence, using the lines $H\alpha$, $H\beta$, $H\gamma$, and $H\delta$. The fall of intensity toward the violet was very marked, the faint $H\delta$ image bringing out only the brightest parts of the prominence as photographed with $H\alpha$ (Figs. 2 and 3, Plate II). $H\beta$ and $H\gamma$ gave intermediate results, approximating those obtained with $H\delta$.

It thus seems probable that the marked intensity of the $H\alpha$ flocculi results from the great strength of the $H\alpha$ line in the chromosphere and prominences. $H\delta$ is strong enough in the middle and sometimes in the upper chromosphere and in the lower parts of bright prominences, to show the hydrogen in these regions when projected on the disk. $H\alpha$, being much more intense, brings before us in plain view a higher region of the solar atmosphere, including the upper chromosphere and bright prominences. Whether these are to appear as bright or dark flocculi, when photographed against the disk, probably depends primarily upon their temperature, though the conditions may not be such as to permit the direct application of KIRCHHOFF's law.

But the photographs bring out a second fact of interest. Although, as has been stated, the flocculi are generally stronger on the $H\alpha$ plates, it cannot be said that these $H\alpha$ images are merely intensified $H\delta$ images, for there is an important point of

difference: dark $H\delta$ flocculi are sometimes replaced on the $H\alpha$ plates by bright flocculi or by apparently neutral spaces. The condition of the hydrogen in such regions thus appears to be the same as in certain stars, whose spectra show $H\alpha$ bright and the more refrangible hydrogen lines dark.¹

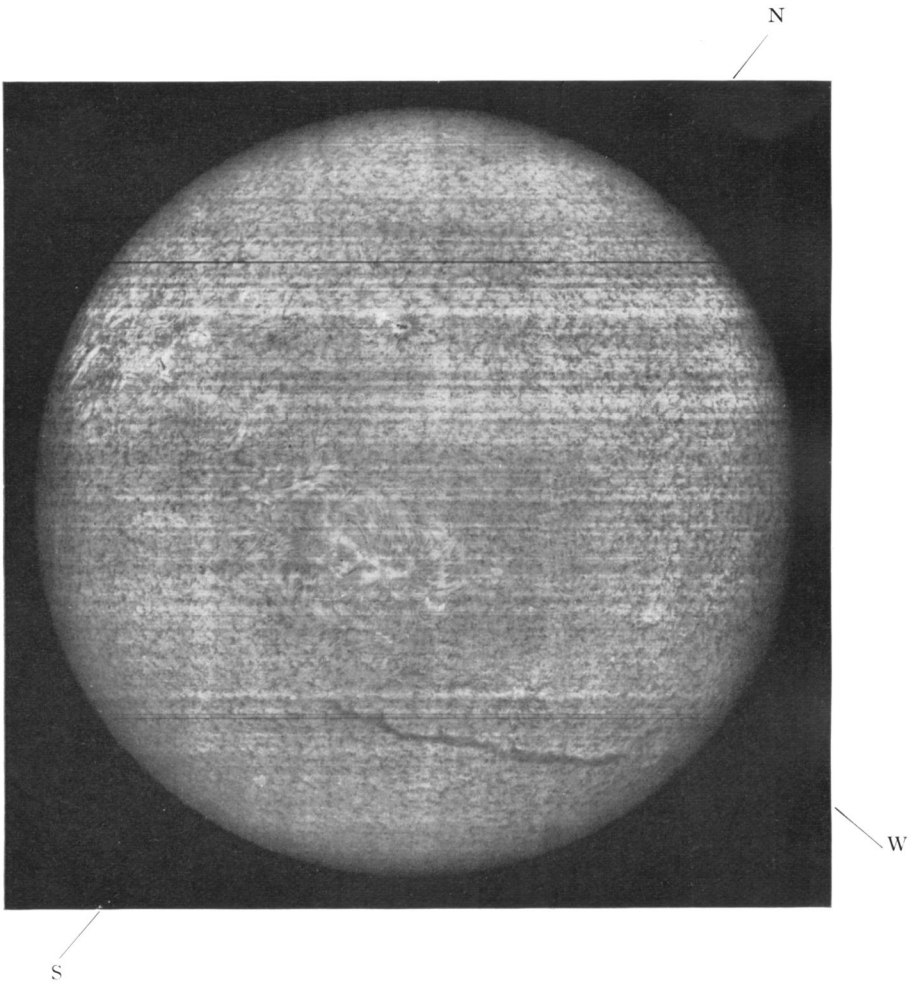
The importance of continuing the work of photographing the Sun with $H\alpha$ was obvious, and I immediately modified the daily programme of observations with this object in view. In the photography of the chromosphere and prominences at the limb, $H\alpha$ was substituted for the H line of calcium, since it was found to give stronger and sharper negatives. For the disk $H\alpha$ was adopted in place of $H\delta$, though work was continued with the latter line long enough to secure a series of photographs for comparison. Later, as more $H\alpha$ plates were needed, the daily series of photographs with the iron line $\lambda 4046$ was discontinued, and all of the observing time of the Snow telescope in the morning devoted to $H\alpha$ work.² In the afternoon this line is also used most of the time, though one plate is made with H_1 and one with H_2 of calcium.

A serious difficulty at once presented itself. Previously only a few photographs had been taken during each of the best observing periods, which last less than two hours in the early morning and late afternoon. Between exposures the mirrors were shielded from sunlight, and electric fans kept a continuous blast of air directed upon them. Even with these precautions there would frequently be a marked change of focal length during an exposure lasting four minutes. The distortion of the mirrors increased during the observations, and strong evidences of astigmatism often appeared before they were completed. Except for occasional eruptions, the calcium, iron, and $H\delta$ flocculi change rather slowly in form, and one or two photographs taken daily with each line sufficed for the investigations in progress. In the case of $H\alpha$ it seemed probable that many photographs, separated by short time-intervals, would be needed to register the phases of

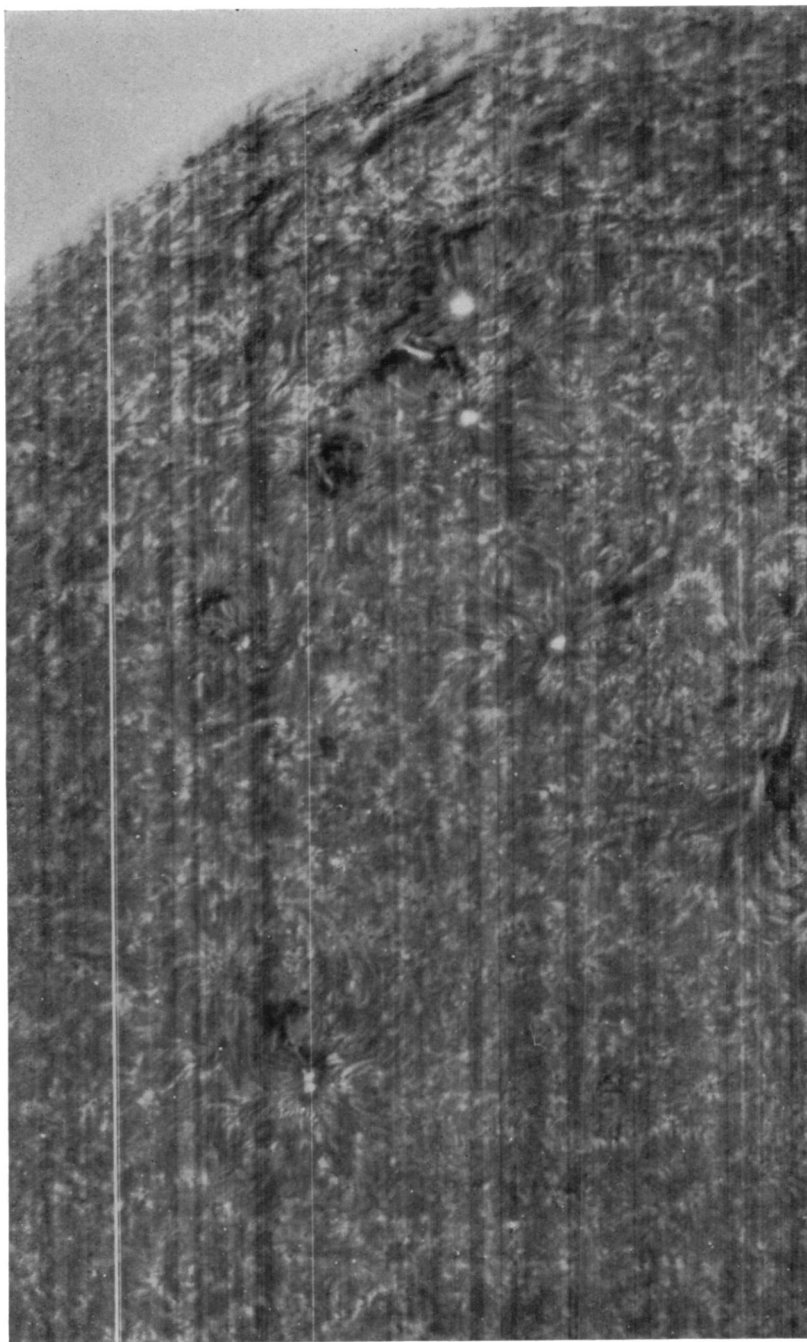
¹ I leave for future consideration the question whether the neutral regions on the $H\alpha$ plates are to be regarded as bright flocculi of reduced intensity. It will also be important to determine whether KAYSER's explanation of the appearance in a stellar spectrum of both bright and dark hydrogen lines (*Astrophysical Journal*, Vol. XIV, p. 313) will apply to solar phenomena.

² Except the short interval required to obtain a direct photograph.

PLATE III



THE SUN, SHOWING THE HYDROGEN ($H\alpha$) FLOCCULI
1908, April 30, 5^h 06^m P. M.



HYDROGEN ($H\alpha$) FLOCCULI SURROUNDING SUN-SPOTS

1908, April 30, 5^h 06^m P. M. Large scale *negative* print showing portion of Plate XXXII, reversed east and west

Scale: Sun's Diameter = 0.3 Meter

rapidly changing phenomena. This would mean almost uninterrupted exposure of the mirrors to sunlight, and such serious distortion that the astigmatism would ruin the photographs.

At this point experience with the tower telescope came in to good advantage. The very thick mirrors used with this instrument are not appreciably distorted in sunlight;¹ hence it seemed probable that by reducing the aperture of the Snow telescope mirrors the increase in their relative thickness would relieve the difficulty. I therefore commenced a series of experiments with different apertures, and finally adopted a 15-inch (38^{cm}) diaphragm for the cœlostat in place of the full aperture of thirty inches (76^{cm}). With this the focal length does not ordinarily change perceptibly during a single exposure. When the mirrors are in sunlight, with very brief interruptions, during a period of an hour, the focal length gradually increases, but the effect of astigmatism is hardly appreciable.

In the work with $H\delta$, the hydrogen flocculi could not be photographed with sufficient contrast unless the very slow "Process" plates (also used for H_1 and H_2) were employed. These plates gave excellent results with $H\alpha$, but could not be used after the aperture had been reduced to fifteen inches without undue increase of exposure time; hence it was necessary to substitute for them SEED's "Gilt Edge" plates, which fortunately serve very well with this line. The first experiments with $H\alpha$ were made about the middle of March. On March 28th the new slits were in place, and the first photographs of the entire disk were obtained. During April the weather was not very favorable, but on April 29th and 30th Mr. ELLERMAN, then in charge of the routine work with the five-foot spectroheliograph, secured some remarkably fine negatives. The one taken on April 30th is reproduced in Plate III. Apart from the whirls, which may be seen to better advantage in Plate IV, this photograph shows in projection an enormous prominence in the southern hemisphere. This also appears, though much less satisfactorily, on the $H\alpha$ photograph of May 1st, and may be traced on the $H\delta$ photograph of the same date (Plate I).

¹ HALE, *Contributions from the Mount Wilson Solar Observatory*, No. 23; *Astrophysical Journal*, Vol. XXVII, p. 204, 1908.

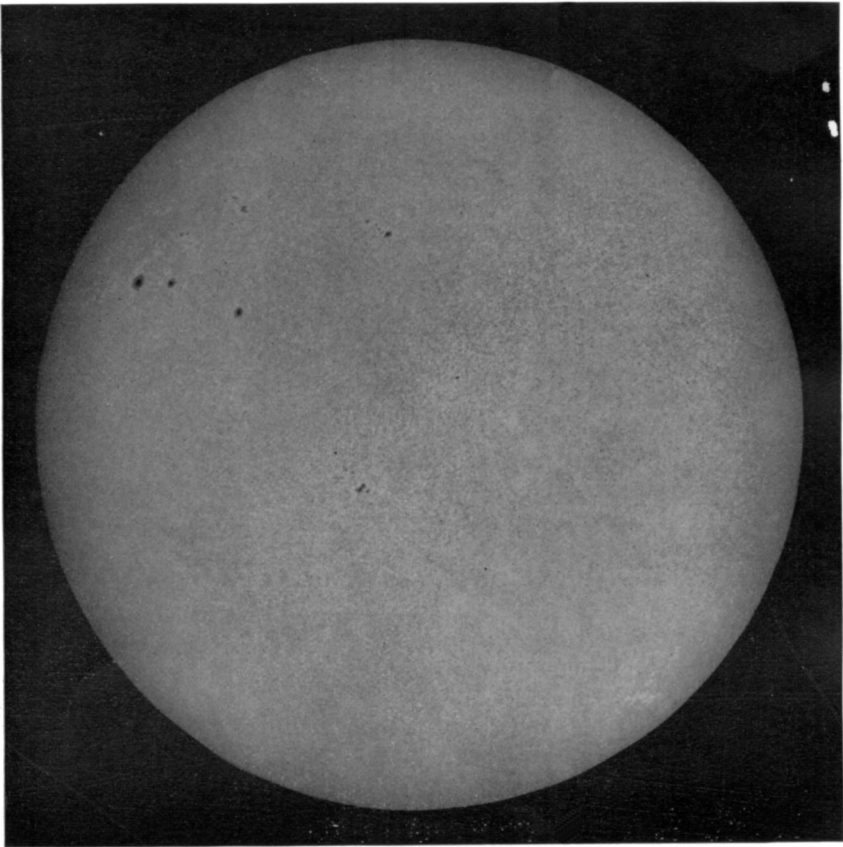
But, in spite of its great intensity and length, this prominence is of minor interest in comparison with the structure shown in Plate IV. This is so definite in form and so unmistakable in character as to satisfy the hopes aroused by the earlier photographs. It seems evident, on mere inspection of these photographs, that sun-spots are centers of attraction, drawing toward them the hydrogen of the solar atmosphere. Moreover, the clearly defined whirls point to the existence of cyclonic storms or vortices.

The most striking of these storms occupies an enormous area in the southern hemisphere, extending from the equator to about 35° south latitude and about 50° in length.¹ Near the center of this region, partly covered by clouds of bright hydrogen, lies the small spot-group shown (from a direct photograph) in Plate V. The corresponding H_2 photograph reveals a large calcium flocculus over the spot-group (Plate VI), but this, though of great size, appears to differ in no essential particular from ordinary calcium flocculi, and gives no evidence of gyratory motion.

A good H_{α} photograph was obtained on April 29th, but it was badly stained in the sensitizing process, and many of the flocculi are hidden by streaks on the negative. Fortunately, the greater part of the large storm area is fairly well shown, so that comparisons with the afternoon photograph of April 30th may be made in the stereocomparator (using the monocular attachment). On account of the changes in form of the flocculi during this interval, the identification of objects suitable for measurement is very difficult and uncertain. Three independent determinations of the positions of certain flocculi on the two plates have been made by Miss WARE. The objects identified on both dates were marked by small dots of ink on the glass side of the negative, and their latitude and longitude measured with the heliomicrometer. When reduced to the same epoch (using for the value of the daily angular motion $\xi = 14^{\circ}.5$, derived from the measurement of 828 points on thirty-five $H\delta$ plates), the plotted results seem to show the existence of a gyratory motion, in a direction opposite to that of the hands of a watch (north, east, south, west). Although

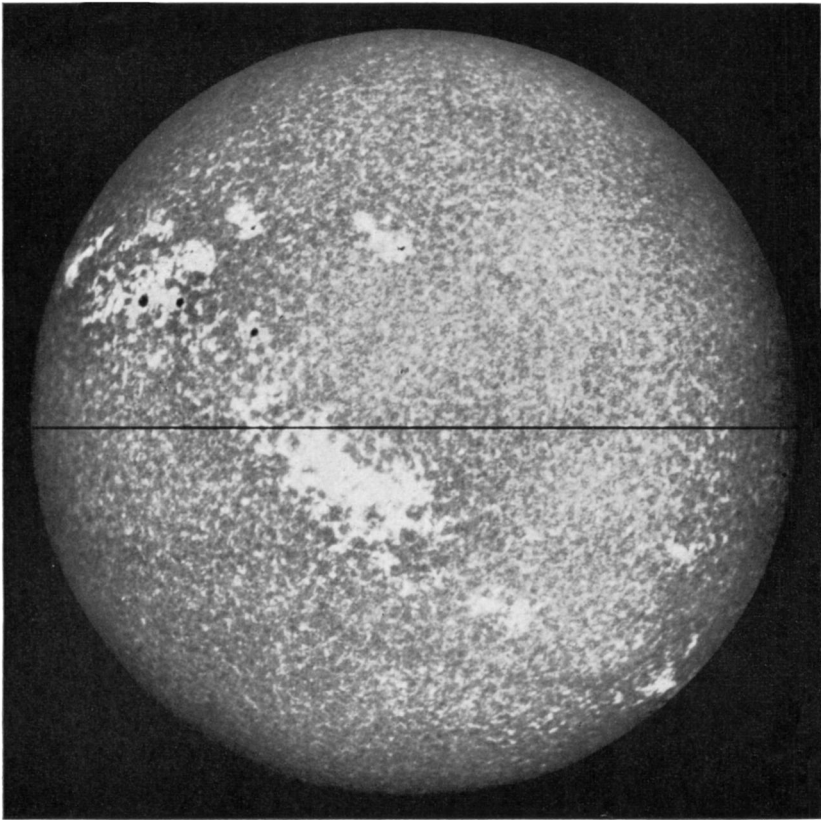
¹ A large-scale plate showing this storm will appear in this *Contribution*, when separately printed. It is unfortunately too large for the page of these *Publications*.

PLATE V



DIRECT PHOTOGRAPH OF THE SUN
1908, April 30, 6^h 25^m A. M.

PLATE VI



THE SUN, SHOWING THE CALCIUM (H_2) FLOCCULI
1908, April 30, 4^h 43^m P. M.

PLATE VII

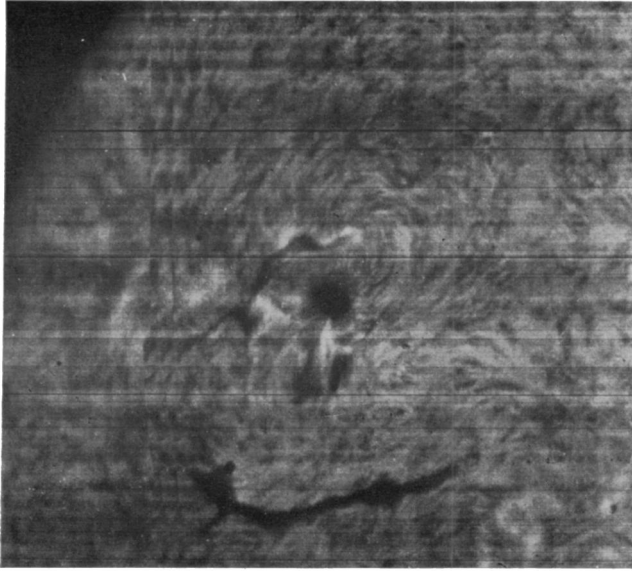


FIG. 1.—SUN-SPOT AND HYDROGEN ($H\alpha$) FLOCCULI
1908, May 29, 4^h 26^m P. M. Scale: Sun's Diameter = 0.3 Meter

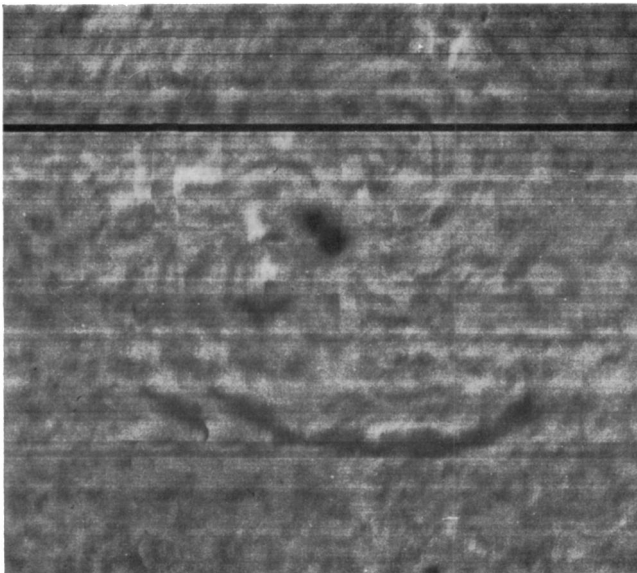


FIG. 2.—SUN-SPOT AND HYDROGEN ($H\alpha$) FLOCCULI
1908, June 2, 6^h 10^m A. M. Scale: Sun's Diameter = 0.3 Meter

most of the points in a given region appear to move together, there are a sufficient number of apparently opposed motions to weaken seriously the value of the evidence. Unfortunately, an $H\delta$ plate taken on the morning of April 30th is not sharp enough to assist in the identifications. Further discussion of these plates is therefore postponed until additional data become available. On account of the complex character of such storms, a large number of photographs, taken at sufficiently short intervals to permit the flocculi to be identified with certainty, will be required to give satisfactory results. As our recent plates show that these storms are of common occurrence, and probably accompany every group containing several spots, there should be no difficulty in obtaining suitable photographs.

In the present paper I wish to illustrate the phenomena recorded with the aid of $H\alpha$ in the neighborhood of a spot which reached the east limb of the Sun at 8^h 16^m A.M. on May 26th, 1908. A photograph of this spot, made by myself with $H\alpha$ on May 29th, at 4^h 26^m P.M., Pacific Standard Time, is reproduced in Fig. 1, Plate VII. The whirl structure, which is clearly shown by this photograph, is also very distinct, though of somewhat different form, on the photograph of May 28th. It is interesting to inquire as to the probable level of the region in which this whirl occurred, and the height of the long dark flocculus south of the spot. For this purpose we may examine photographs of the chromosphere and prominences at the limb, taken on May 25th, 26th, and 27th. In the first of these, made on May 25th, at 9^h 18^m A.M. (No. 4142), a long, narrow prominence, extending toward the north, rises from the limb at position-angle 92°, a point about one degree north of where the spot would be. It makes an angle of about 12° with the limb, and fades out at the upper end, its length being approximately 90'' (geocentric). There are other small filamentary prominences in the region extending about 7° north of the spot, and smaller elevations in the chromosphere to the south. At position-angle 98° a bright prominence rises to a height of about 20'', and then slopes to the chromospheric level at position-angle 107°. Near its southern end is an independent filamentary prominence about 55'' high. On May 26th, at 6^h 38^m A.M. (No. 4144), the prominences shown in Fig. 1,

Plate II, were photographed at the east limb. The lowest point in the chromosphere on this photograph corresponds to the position (P. A. 93°) where the spot crossed the limb about two hours later. It will be seen that these prominences, which extend from position-angle 82° to 106° , cover much of the region in which the whirl structure of Plate VII appears. The prominence south of the spot is very bright and its highest point reaches an elevation of about $35''$. On May 27th, at $5^h 22^m$ P.M. (No. 4152), a prominence about $25''$ high extends from position-angle 105° to 109° . This is doubtless the eastern extremity of the strong flocculus in Plate VII, which may there be seen curving toward the spot.

We may now pass in rapid survey the more important photographs of the disk. On May 28th, at $6^h 58^m$ A.M. (No. 4157), the spot is near the east limb and the whirls are well shown. To the east of the spot is a long, narrow line of bright hydrogen. On May 29th, at $6^h 24^m$ A.M. (No. 4171), the whirls are very distinct and differ in many respects from those shown on May 28th. Eruptive regions of bright hydrogen are seen southeast and west of the spot. The eastern end of the long, dark flocculus is changing in form, and bridges are appearing over the spot. Negative No. 4175, taken $1^h 19^m$ later, seems to show distinct changes in the whirls, though they are not measurable. On May 29th, at $4^h 26^m$ P.M. (No. 4176), the whirls resemble those shown in negative No. 4175, but exhibit some marked changes. An eruption, which appears on the former plate southeast of the spot, continues, but is changed in form and less brilliant than before. A strong eruption, of peculiar form, appears southwest of the spot, and bright hydrogen to the northeast. Strong dark flocculi have also developed at many points around the spot. The eastern end of the long, dark flocculus is still changing, and a projection appears west of its center (see Plate VII). A negative taken on the same day, at $5^h 13^m$ P.M. (No. 4178), shows further changes both in the bright and dark structure, especially in the region southwest of the spot. A fork has developed in the western end of the long, dark flocculus, and a small but very dark flocculus appears just west of the spot. Another photograph (No. 4179), the first exposure of which was made at $5^h 26^m$ P.M., shows a bright eruption west of the spot, where the small,

dark flocculus appears on No. 4178. The eruption underwent considerable change of form while the five exposures on this plate, separated by intervals of a few minutes, were being made. At 6^h 04^m P.M. negative No. 4181 shows that the eruption had subsided, and brings out other definite changes in structure near the spot. The small, dark flocculus has disappeared. On May 31st, at 8^h 09^m A.M. (No. 4188), the fork at the western extremity of the long, dark flocculus has partially closed. No eruptions appear west of the spot, but there are bright ones to the southeast. Other important changes are evident, and the two bridges across the spot are conspicuous. On June 1st, at 6^h 30^m A.M. (No. 4189), the fork at the western end of the long, dark flocculus appears more nearly as it did in negative No. 4181, and the two bridges over the spot are very marked. A negative taken fifteen minutes later (No. 4190), shows distinct changes, especially in the region south and southeast of the spot. At 5^h 08^m P.M. of the same day negative No. 4193 shows a more distinct whirl near the spot, and the long, dark flocculus appears to be growing shorter at its eastern end. On June 2d, at 6^h 10^m A.M. (No. 4196), the whirling structure is very marked and more nearly symmetrical about the spot, which is divided into two parts (Fig. 2, Plate VII). At 7^h 27^m A.M. (No. 4198), the whirl is also very marked and somewhat changed in form.

Up to this time the changes, while in many cases rapid, were not especially violent. On June 3d, in an interval of about ten minutes, a remarkable transformation occurred. The long, dark flocculus, which had been gradually changing in form and position, was suddenly drawn into the spot. As Fig. 2, Plate VII, illustrates, the whirls were very conspicuous on the preceding day. A series of photographs, nine of which were made on negative No. 4201, between 4^h 48^m 09^s P.M. and 5^h 13^m 54^s P.M., and one, showing the entire disk, on negative No. 4202, at 5^h 22^m P.M., records the changes which took place during this time. These photographs were taken by Dr. C. E. ST. JOHN, who joined the observatory staff in May, and is sharing with me the observational work with the five-foot spectroheliograph during Mr. ELLERMAN'S absence on vacation. Three of these have been selected for reproduction. Fig. 1, Plate VIII, is enlarged from a photograph made at

4^h 58^m 16^s P.M. (time of transit of spot across collimator slit of spectroheliograph). At 5^h 01^m 21^s the large, dark flocculus is apparently unchanged in form. At 5^h 04^m 21^s a photograph, which is not quite so well defined, gives no certain evidence of change. The next photograph, made at 5^h 07^m 06^s, clearly shows the development of a fork at the eastern end of the flocculus, with traces of a very faint curved extension toward the larger spot. The position of the end of the fork (C), as measured on this photograph, is given below, but the extension is too faint to be measured with certainty. The next photograph, made at 5^h 10^m 52^s, shows the fork and part of the extension, but the definition is poor and the position of the end of the extension uncertain. The last photograph on this plate, made at 5^h 13^m 54^s, is reproduced in Fig. 2, Plate VIII. This admits of fairly satisfactory measurement, the results of which are given below. The spot region on negative No. 4202, made at 5^h 22^m P.M. (time of transit of spot), is reproduced in Fig. 1, Plate IX. Here the definition and contrast are also poor, but the extension, reaching nearly to the spots, is sufficiently well shown, as well as a dark flocculus which developed southeast of the smaller spot.

With the aid of the monocular attachment of the stereo-comparator, I have made a careful examination of all the photographs, and Miss WARE has measured the positions of the long, dark flocculus with the heliomicrometer. If we call *A* the western extremity of this flocculus, *B* its eastern extremity, and *C* its point of nearest approach to the spot, we have the following results of the measurements, which also include the positions of the two spots:—

TABLE I.

Negative No.	Date.	Point.	Longitude.	Latitude.	Remarks.
4176	May 29, 1908 4 ^h 26 ^m P.M.	A	32°.0 E	5°.8 S	B and B' are the two extremities of eastern end of flocculus.
		B	48 .6	13 .6	
		B'	46 .7	12 .8	
		Spot	45 .8	3 .0	
		Spot	44 .4	3 .1	
4189	June 1, 1908 6 ^h 30 ^m A.M.	A	3 .9 W	5 .5 S	
		B	13 .0 E	13 .1	
		Spot	10 .2	2 .3	
		Spot	8 .6	2 .6	

PLATE VIII

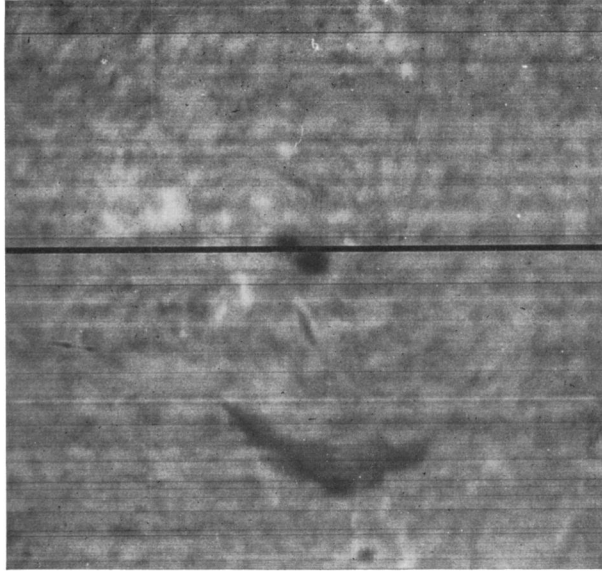


FIG. 1.—SUN-SPOT AND HYDROGEN ($H\alpha$) FLOCCULI
1908, June 3, 4^h 58^m 16^s P. M. Scale: Sun's Diameter = 0.3 Meter

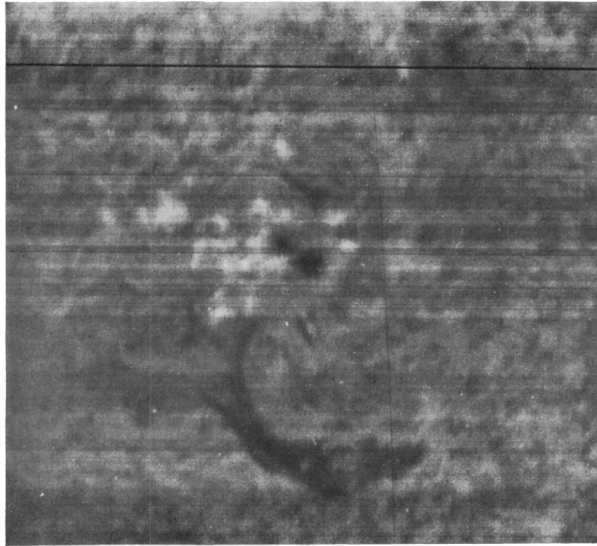


FIG. 2.—SUN-SPOT AND HYDROGEN ($H\alpha$) FLOCCULI
1908, June 3, 5^h 13^m 54^s P. M. Scale: Sun's Diameter = 0.3 Meter

PLATE IX

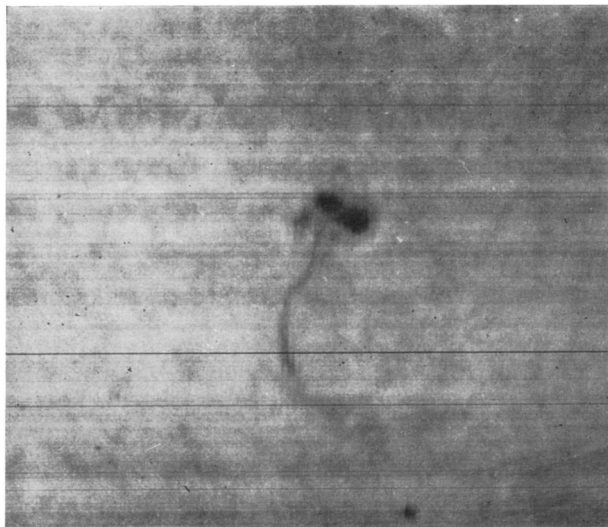


FIG. 1.—SUN-SPOT AND HYDROGEN ($H\alpha$) FLOCCULI
1908, June 3, 5^h 22^m P. M. Scale: Sun's Diameter = 0.3 Meter

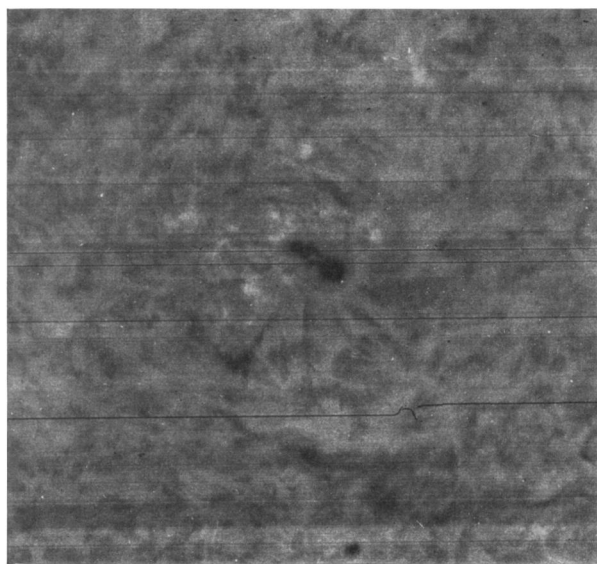


FIG. 2.—SUN-SPOT AND HYDROGEN ($H\alpha$) FLOCCULI
1908, June 4, 6^h 12^m A. M. Scale: Sun's Diameter = 0.3 Meter

TABLE I—Continued.

Negative No.	Date.	Point.	Longitude.	Latitude.	Remarks.
4193	June 1, 1908 5 ^h 08 ^m P.M.	A	9° .7 W	4° .0 S	
		B	6 .4 E	12 .9	
		Spot	3 .5	3 .0	
		Spot not measurable.			
4196	June 2, 1908. 6 ^h 10 ^m A.M.	A	16 .9 W	5 .5 S	A and A' are the two extremities of western end of flocculus.
		A'	16 .2	4 .5	
		B	2 .9	12 .4	
		Spot	2 .8	2 .8	
		Spot	4 .1	3 .1	
4201, Exp. 5.	June 3, 1908 5 ^h 01 ^m 21 ^s P.M.	A	38 .3 W	5 .8 S	
		B	23 .9	11 .1	
		Spot	22 .5	2 .6	
		Spot	24 .2	2 .7	
4201, Exp. 6.	June 3, 1908 5 ^h 04 ^m 21 ^s P.M.	A	35 .8 W	8 .2 S	
		B	23 .6	11 .2	
		C	25 .5	11 .1	
		Spot	22 .5	2 .6	
		Spot	24 .4	2 .8	
4201, Exp. 7.	June 3, 1908 5 ^h 07 ^m 06 ^s P.M.	A	35 .9 W	8 .1 S	
		B	23 .5	11 .0	
		C	24 .0	9 .2	
		Spot	22 .5	2 .5	
		Spot	24 .4	2 .7	
4201, Exp. 9.	June 3, 1908 5 ^h 13 ^m 54 ^s P.M.	A	35 .5 W	8 .0 S	
		B	23 .6	11 .0	
		C	23 .6	6 .2	
		Spot	22 .6	2 .6	
		Spot	24 .4	2 .7	
4202	June 3, 1908 5 ^h 22 ^m P.M.	C	23 .0 W	3 .5 S	C approaches east- ern spot. C' approaches west- ern spot.
		C'	23 .8	3 .4	
		Spot	24 .5	2 .6	
		Spot	22 .7	2 .5	

If we now take the measured differences in longitude and latitude of the large spot and the points *A*, *B*, and *C* respectively, and compute the corresponding distances, we have the results given in Table II:—

TABLE II.

No.	Date.	Longitude.		Latitude.		Distance.	
		A—Spot.	B—Spot.	A—Spot.	B—Spot.	A—Spot.	B—Spot.
4176	May 29, 4 ^h 26 ^m P.M.	+ 12° 4	+ 4° 2	+ 2° 7	+ 10° 5	12.7	11.3
4189	June 1, 6 30 A.M.	+ 12.5	+ 4.4	+ 2.9	+ 10.5	12.8	11.4
4193	June 1, 5 08 P.M.	+ 13.2	+ 2.9	+ 1.0	+ 9.9	13.2	10.3
4196	June 2, 6 10 A.M.	+ 12.8	+ 1.2	+ 2.4	+ 9.3	13.0	9.4
		+ 12.1		+ 1.4		12.1	
4201	June 3,—						
	Exp. 5, 5 01 21 P.M.	+ 14.1	+ 0.3	+ 3.1	+ 8.4	14.4	8.4
	Exp. 6, 5 04 21 P.M.	+ 11.4	+ 0.8	+ 5.4	+ 8.4	12.6	8.4
	Exp. 7, 5 07 06 P.M.	+ 11.5	+ 0.9	+ 5.4	+ 8.3	12.7	8.3
	Exp. 9, 5 13 54 P.M.	+ 11.1	+ 0.8	+ 5.3	+ 8.3	12.3	8.3
4202	June 3, 5 22 P.M.						
		C—E. Spot		C—E. Spot		C—E. Spot	
		= 0.3		= 0.8		= 1.0	
		C'—W. Spot		C'—W. Spot		C'—W. Spot	
		= 0.7		= 1.0		= 1.1	

These results show that the long, dark flocculus gradually shortened, its eastern extremity apparently moving inward along the flocculus, while the distance of its western extremity from the spot did not change in a systematic manner. Accuracy of measurement is out of the question, as the flocculus varied so much in form from day to day that there can be no certainty in the identification of points that appear to correspond. A comparison of the series of photographs taken during the period of rapid development shows that the form and position of the main body of the flocculus did not greatly alter in this short interval, though the maximum of intensity moved rapidly toward the spots, leaving the body of the flocculus very faint. Even on these photographs, however, the velocity of the motion toward the spot cannot be precisely measured, partly because of the difficulty of determining where the extension ends, and also because the time of the beginning of the phenomenon doubtless did not exactly coincide with the moment of exposure 6. Between exposures 6 and 7 we find for the point *C* a change of $1^{\circ}.9$ in latitude and $1^{\circ}.5$ in longitude. This corresponds to a motion of $2^{\circ}.4$ in 195 seconds, or 177^{km} per second. Between exposures 7 and 9, in an interval of 408 seconds, there was a change of $3^{\circ}.0$ in latitude and $0^{\circ}.4$ in longitude, giving a velocity of 89^{km} per second. Eight minutes later¹ the extension had divided and moved nearly to the spots, the resultant motion for each extremity being $2^{\circ}.8$, giving a velocity of 71^{km} per second.

In order to check these measures, the stereocomparator was used to mark all of the points on a single plate, which was then measured differentially. The resulting velocities came out 140^{km} , 86^{km} , and 76^{km} per second respectively. Since the errors due to imperfect superposition in the stereocomparator should not differ markedly from those arising from a similar source in the heliomicrometer, the second set is given the same weight as the first. The differences among the three velocities cannot be trusted, though the evidence favors the view that the first velocity was actually higher than the others. The mean of the six measures (106^{km}) will at least serve to give the order of the maximum velocity in the vortex.

¹ The time of negative No. 4202 is recorded only to the nearest minute.

The appearance of the spot and surrounding region thirteen hours after the rapid changes described above is shown in Fig. 2, Plate IX. The straight radial lines in this photograph are in marked contrast to the curved structure previously shown. The eastern of the more plainly marked radial lines is found by measurement to be a short distance to the east of the extension from the large flocculus to the spots shown in Fig. 2, Plate VIII. The forked connection to the two spots has disappeared and a strong, dark flocculus has developed at the southern extremity of the radial line, mainly on its eastern side. With the stereocomparator the main body of the large flocculus is found to resemble its former appearance in some particulars, but the distribution of intensities is very different and many changes in outline have occurred. In the photograph of June 5th, at 7^h 05^m A.M. (No. 4220), the radial structure surrounding the spots is greatly altered and the flocculus, no longer recognizable, has developed a large extension toward the west (Fig. 1, Plate X¹). A notable feature of this photograph is the amount of bright eruptive hydrogen in the region surrounding the two spots. Some eruptive matter also appears in the photographs of the preceding day, but here it is greatly augmented. A photograph taken on the same day, at 5^h 19^m P.M. (No. 4227), is reproduced in Fig. 2, Plate X. It will be seen that the eruptions continue, and that the dark flocculi have undergone further important changes. The most notable of these is the connection which appears to be re-established between the two spots and the dark flocculus south of them. Apparently the dark hydrogen is again being drawn into the spots. On June 7th, at 7^h 56^m A.M. (No. 4244), a faint prominence appears on the limb south of the position of the spot. On June 8th, at 7^h 42^m A.M., negative No. 4252 shows a group of prominences closely resembling in form those reproduced in Fig. 1, Plate II, but very much less brilliant. On June 9th no prominence was photographed in this region.

As already remarked, the distance from the spot of the western extremity of the large flocculus did not vary systematically. The eastern extremity, on the contrary, commenced

¹ There is a defect in this plate near the spots.

PLATE X

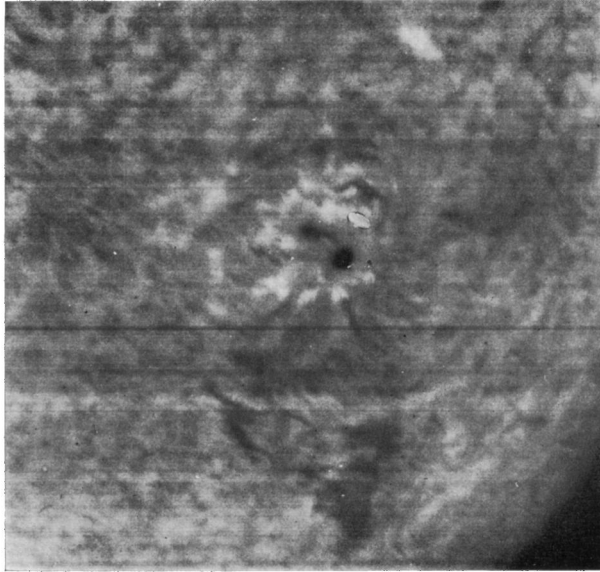


FIG. 1.—SUN-SPOT AND HYDROGEN ($H\alpha$) FLOCCULI
1908, June 5, 7^h 05^m A. M. Scale: Sun's Diameter = 0.3 Meter

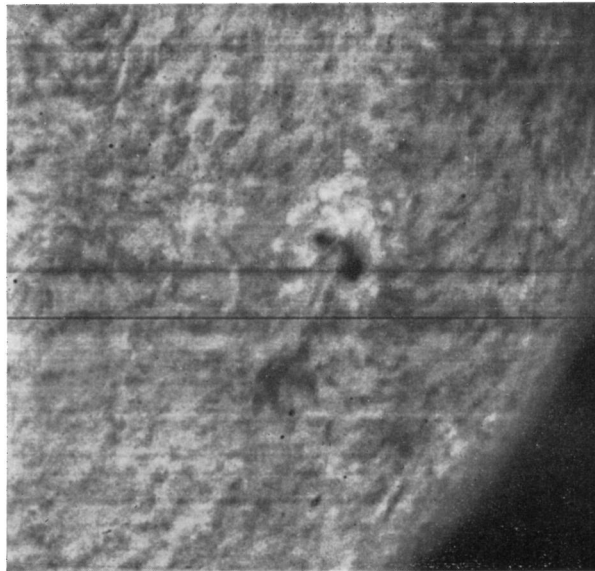


FIG. 2.—SUN-SPOT AND HYDROGEN ($H\alpha$) FLOCCULI
1908, June 5, 5^h 19^m P. M. Scale: Sun's Diameter = 0.3 Meter

on June 1st to approach the spot, and continued to do so until the sudden change occurred on June 3d. Up to this time the velocity, instead of showing signs of acceleration, was apparently retarded, but the changing form of the flocculus leaves this point uncertain. On the photograph of May 29th (No. 4176) the whirl is most conspicuous north of the spot, where its extreme distance is about equal to that of the western end of the large flocculus. Apparently, however, the flocculus did not fall completely under the influence of the vortex until June 1st, when its eastern extremity was $11^{\circ}.4 = 140,000^{\text{km}}$ from the spot. The fact that the minimum distance of the western end always exceeded this quantity may account for its escape.

In view of the nature of the phenomena described in this paper, and the fact that evidences of whirls or radial structure have been shown, in connection with several different spots, on a large number of $H\alpha$ photographs, one is greatly tempted to enter at once into a discussion of the sun-spot theories of FAYE, REYE, EMDEN, HALM, ECKHOLM, BIGELOW, etc., all of which assume the existence of cyclones or vortices within the photosphere or the solar atmosphere. It is the part of prudence, however, to defer such discussion until our daily increasing supply of photographs is considerably enlarged. Moreover, I have devised improved methods for comparing photographs, which should facilitate the identification of objects for measurement, and experiments are also in progress with the purpose of bringing more clearly before the eye the nature of the changes which take place within the vortices. A simple kinetoscope has been advantageously used to observe the rapidly changing phenomena of June 3d, and more elaborate apparatus of this kind will soon be available.

It may be well to direct attention, however, to certain points which have been noted:—

- (1) In the series of photographs (on negatives Nos. 4201 and 4202), which shows the large flocculus in the act of being drawn into the spots, the small flocculi near the spots remain almost unchanged in position, perhaps because of difference of level.
- (2) Except in the case of the large flocculus, attempts to detect evidences of motion toward the spots have not yet proved successful, even along apparent lines of flow.

(3) Negative No. 4196, taken on June 2d, shows a dark comet-like object (apparently defining a line of flow) intersecting a bright eruptive flocculus. The appearance suggests that the eruption does not rise to the level of the vortex.

(4) Photographs of the $H\alpha$ line across bright flocculi, made in the second and third order spectra of the 30-foot tower spectrograph, indicate that this line has a complex structure which will require careful investigation.

(5) Since the velocity of the hydrogen drawn into the vortex is of the same order as that of eruptive prominences, distortions of the hydrogen lines at the limb may be due to the motion of this gas in vortices. If the line of sight were to pass through a vortex, distortions toward violet and red observed at the same point might result from motions of approach and recession on opposite sides of the vortex.

(6) The appearance of numerous hydrogen eruptions after the event of June 3d suggests that the hydrogen drawn down by the vortex subsequently rose to the surface in the neighborhood of the spots.

(7) In view of the fact that the distribution of the hydrogen flocculi frequently resembles that of iron filings in a magnetic field, it is interesting to recall the exact correspondence between the analytical relations developed in the theory of vortices and in the theory of electro-magnetism.¹

(8) The gradual separation of the spots should not be overlooked.

Without entering at present into further details, a single suggestion relating to the possible existence of magnetic fields on the Sun may perhaps be offered. We know from the investigations of ROWLAND that the rapid revolution of electrically charged bodies will produce a magnetic field, in which the lines of force are at right angles to the plane of revolution. Corpuscles emitted by the photosphere may perhaps be drawn into vortices,² or a preponderance of positive or negative ions may result from some other cause. When observed along the lines of force, many of the lines in the spot spectrum should be double, if they are produced in a strong magnetic field. Double lines, which look like reversals, have recently been

¹ See LAMB, "Hydrodynamics," third edition, p. 201.

² J. J. THOMSON, "Conduction of Electricity through Gases," p. 164.

photographed in spot spectra with the 30-foot spectrograph of the tower telescope,¹ confirming the visual observations of YOUNG and MITCHELL. It must be determined whether the components of these double lines are circularly polarized in opposite directions, or, if not, whether other less obvious indications of a magnetic field are present. I shall attempt the necessary observations as soon as a suitable spot appears on the Sun.

MT. WILSON SOLAR OBSERVATORY, June 20, 1908.

REMARKS ON THE PLATES.

As it seems to be impossible to obtain illustrations which accurately represent the original negatives, certain remarks regarding the plates are required.

Plate I. Both figures are fairly satisfactory, except that the limb of the Sun, in the lower right-hand corner, is not properly shown.

Plate II, Fig. 1. The position-angles of various points in the prominences are given in the text of the article. The faint parallel lines, which make an acute angle with the Sun's limb, are due to a slight irregularity in the motion of the spectroheliograph.

Plate II, Fig. 2. The black dots are defects produced in the sensitizing process.

Plate II, Fig. 3. The parallel lines are due to the cause mentioned above.

Plate III. This plate will serve to give a general idea of the appearance of the *H α* photograph of April 30th, but fails to show the flocculi in their proper intensity. Although many bright flocculi appear to be present, especially in the upper part of the image, the original negative actually shows very few of these objects, the most conspicuous ones being in the midst of the great storm area in the southern hemisphere. For details, see Plate IV. The parallel vertical bands are due to a periodic motion of the spectroheliograph.

Plate IV. As it was found by experiment that the flocculi on the photograph of April 30th are most accurately represented on a negative print, Plate IV is reproduced in this way. Thus the light objects on this plate represent the dark *H α* flocculi. The limb is not well reproduced and certain regions near the spots and in the lower part of the plate are too black.

Plate V. The scale is so small that this illustration serves merely to indicate the distribution of the sun-spots on April 30th, and the apparently insignificant nature of the group lying within the great storm area (near the center). The orientation is the same as for Plate III.

¹ HALE, *Contributions from the Mount Wilson Solar Observatory*, No. 23; *Astrophysical Journal*, Vol. XXVII, p. 204, 1908.

Plate VI. This gives a fair idea of the appearance of the calcium (H_2) flocculi, though the limb is not well reproduced. The orientation is the same as for Plate III.

Plate VII, Fig. 1. The only bright flocculi that should appear in this figure are those in the neighborhood of the spot.

Plate VII, Fig. 2. The background comes out too bright, giving the appearance of bright flocculi in regions where they are not present. The only objects of this class shown by the original negative are very conspicuous in the figure.

Plate VIII, Fig. 1. This gives a fair idea of the original negative, the contrast of which is not very strong.

Plate VIII, Fig. 2. The contrast of the original is much stronger than in the case of Fig. 1, hence the bright flocculi near the spot are relatively too conspicuous. The background in the upper part of the figure is also too bright.

Plate IX, Fig. 1. The original is lacking in contrast. The region to the left of the spot should be much darker than it appears in the cut.

Plate IX, Fig. 2. This is a fairly satisfactory reproduction, though the bright flocculi should be somewhat stronger.

Plate X, Fig. 1. Except for a defect in the photograph, the bright flocculi surrounding the spot are fairly well shown. In other parts of the figure, however, the background comes out too bright.

Plate X, Fig. 2. This is a fairly satisfactory reproduction, though the background is too bright in various places.

SOLAR VORTICES AND THE ZEEMAN EFFECT.

BY GEORGE E. HALE.

In a previous paper I have described and illustrated the vortices surrounding sun-spots recently photographed on Mt. Wilson with the Snow telescope and five-foot spectroheliograph.¹ While studying the vortices, it occurred to me that the rapid revolution of electrically charged particles in the solar atmosphere should produce a magnetic field within a sun-spot (Rowland effect), if a preponderance of negative or positive ions be assumed. Such a condition might result from the emission of corpuscles by the photosphere,² or, as Professor E. F. NICHOLS has suggested to me, from centrifu-

¹ "Solar Vortices," *Contributions from the Mount Wilson Solar Observatory*, No. 26, *Publications A. S. P.*, No. 121.

² J. J. THOMSON, "Conduction of Electricity through Gases," p. 164.